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80 West End Avenue / New York, New York 10023 / (212) 873-4000

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TECHNICAL REPORT T-2/306-3-14

PRESENT STATUS OF THE RRI SLANT-PATH ABSORPTION MODEL (SLAM) COMPUTER PROGRAM

By D. Koppel

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AUTHORIZATION

This report describes work performed at Riverside Research Institute by D. Koppel with the assistance of M. Greenebaum and S. Rosenberg. The report was written by D. Koppel.

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Submitted by:

M. King

M. King
Manager, Optics
Laboratory

Approved by:

M. Arm
Research Director

ABSTRACT

A computer program (SLAM) is described which calculates the attenuation by air of microwave and submillimeter radiation. Besides the horizontal attenuation, the vertical attenuation from various levels down to the ground and out into space is calculated for a fixed frequency. The line profile and atmospheric model can be selected from among several. Comparison is made with other calculations, and with experiments. Possibilities for improving the program are discussed.

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I. INTRODUCTION

As part of an atmospheric propagation study sponsored by DARPA, RRI has developed a computer program to calculate atmospheric attenuation in the microwave and submillimeter regions of the electromagnetic spectrum. This program is intended for analyzing communications systems and other applications in this spectral region not only at ground level but also with transmitters and receivers at higher altitudes. Hence, emphasis has been placed on calculating the total attenuation down to the ground and out into space at any given frequency, at a set of reasonably spaced atmospheric levels. The program is written in FORTRAN[1] and may be looked upon as a modification of a program originated by McClatchey, et. al. of AFCRL.[2]

The inputs to the program consist of an atmospheric model, a spectral line compilation, and a control file giving the choice of parameters to be used in the calculations. Currently six atmospheric models are available for use. These are the "Tropical," "Midlatitude Summer," "Midlatitude Winter," "Subartic Summer," "Subarctic Winter," and "U.S. Standard Atmosphere, 1962" all as formulated by McClatchey, et. al.[3]. The "Midlatitude Winter" model is reproduced in Table I. This model gives the pressure, temperature, and water vapor and ozone contents as a function of altitude. The other species currently represented in the spectral line compilation, namely oxygen and carbon monoxide, are assumed to have constant mixing ratios. Other atmospheric models can be used by changing the input file. The spectral line compilation

TABLE I

MIDLATITUDE WINTER MODEL USED IN SLAM PROGRAM

HEIGHT (KM)	PRESSURE (MBAR)	TEMP (K)	WATER (G/M**3)	OZONE (G/M**3)
0.	1.0180E+03	272.2	3.5 E+00	6.0000E-05
1.	8.973 E+02	268.7	2.5 E+00	5.4 E-05
2.	7.897 E+02	265.2	1.8 E+00	4.9 E-05
3.	6.938 E+02	261.7	1.2 E+00	4.9 E-05
4.	6.081 E+02	255.7	6.6 E-01	4.9 E-05
5.	5.313 E+02	249.7	3.8 E-01	5.8 E-05
6.	4.627 E+02	243.7	2.1 E-01	6.4 E-05
7.	4.016 E+02	237.7	8.5 E-02	7.7 E-05
8.	3.473 E+02	231.7	3.5 E-02	9.0 E-05
9.	2.992 E+02	225.7	1.6 E-02	1.2 E-04
10.	2.568 E+02	219.7	7.5 E-03	1.6 E-04
11.	2.199 E+02	219.2	6.9 E-03	2.1 E-04
12.	1.882 E+02	218.7	6.0 E-03	2.6 E-04
13.	1.610 E+02	218.2	1.8 E-03	3.0 E-04
14.	1.378 E+02	217.7	1.0 E-03	3.2 E-04
15.	1.178 E+02	217.2	7.6 E-04	3.4 E-04
16.	1.007 E+02	216.7	6.4 E-04	3.6 E-04
17.	8.610 E+01	216.2	5.6 E-04	3.9 E-04
18.	7.350 E+01	215.7	5.0 E-04	4.1 E-04
19.	6.280 E+01	215.2	4.9 E-04	4.3 E-04
20.	5.370 E+01	215.2	4.5 E-04	4.5 E-04
21.	4.580 E+01	215.2	5.1 E-04	4.3 E-04
22.	3.910 E+01	215.2	5.1 E-04	4.3 E-04
23.	3.340 E+01	215.2	5.4 E-04	3.9 E-04
24.	2.860 E+01	215.2	6.0 E-04	3.6 E-04
25.	2.430 E+01	215.2	6.7 E-04	3.4 E-04
30.	1.110 E+01	217.4	3.6 E-04	1.9 E-04
35.	5.180 E+00	227.8	1.1 E-04	9.2 E-05
40.	2.530 E+00	243.2	4.3 E-05	4.1 E-05
45.	1.290 E+00	258.5	1.9 E-05	1.3 E-05
50.	6.820 E-01	265.7	6.3 E-06	4.3 E-06
70.	4.670 E-02	230.7	1.4 E-07	8.6 E-08
100.	3.000 E-04	210.2	1.0 E-09	4.3 E-11

used has been taken in large part from the first section of a magnetic tape obtained from AFCRL[4]. In most of the 0 to 550 cm^{-1} spectral region under consideration, i.e., in the "pure rotation" region below 430 cm^{-1}, this tape includes only water, ozone, and the microwave spectrum of oxygen. Consequently, this compilation has been modified by adding the results recently obtained at RRI on the submillimeter and microwave spectrum of oxygen[5] and on the rotational spectrum of carbon monoxide.[6] (The oxygen lines were added for three isotopic species: $^{16}O^{16}O$, $^{16}O^{18}O$ and $^{18}O^{18}O$. Both the ground vibrational level and the first vibrationally excited state were taken into accound for $^{16}O^{16}O$.) A sample of the compilation is shown in Table II. The first column gives the frequency in cm^{-1}; the second column, the (modified) integrated line strength at 296K, in cm^{-1}/molecules cm^{-2} (modification described below); the third column, the pressure coefficient of the line half-width in cm^{-1}/atm; the fourth column, the energy of the lower state in cm^{-1}; the fifth column, the date (month and year) of insertion into the file; the sixth column, the isotope concerned (e.e., 68 is $O^{16}O^{18}$); and the seventh column, the molecular constituent, the integers M=1,3,5,7 standing for water vapor, ozone, carbon monoxide, and oxygen, respectively.

The data on the tape received from AFCRL was first converted to the 9-track format required by the Xerox Sigma 9 computer and then was placed into a magnetic disc file and converted from BCD to binary format (for increased speed). The control file (Table III) contains information on the first and last frequency to be used, the frequency increment, the quantity BOUND (which gives the frequency range within which lines are to be summed to obtain the attenuation at a fixed frequency), the choice of the spectral line profile to be used, and a choice of: (a) summing over all the molecular constituents to get the total attenuation (zero in the sixth column), (b) just considering the

TABLE II

Sample of Spectral Line Compilation

FREQ	STRENGTH	HALF WIDTH	ENERGY	DATE	ISO TOPE	CONSTITUENT
NO OF RECORDS=		40				
.307	.121E-22	.1100	205.328	102	666	3
.341	.199E-22	.1100	50.302	102	666	3
.369	.199E-22	.1100	8.022	102	666	3
.496	.183E-22	.1100	281.833	102	666	3
.539	.157E-22	.1100	345.692	102	666	3
.742	.121E-21	.0811	446.512	23	161	1
.796	.355E-22	.1100	171.501	102	666	3
.856	.192E-22	.1100	127.264	102	666	3
.966	.326E-22	.1100	301.671	102	666	3
1.002	.529E-22	.1100	128.119	102	666	3
1.007	.289E-22	.1100	100.572	102	666	3
1.018	.169E-22	.1100	157.147	102	666	3
1.202	.395E-22	.1100	241.831	102	666	3
1.262	.683E-22	.1100	156.903	102	666	3
1.429	.254E-22	.1100	2.519	102	666	3
1.456	.492E-22	.1100	77.082	102	666	3
1.463	.110E-22	.1100	702.316	102	666	3
1.497	.175E-22	.1100	190.212	102	666	3
1.650	.578E-27	.0320	2460.774	75	66	7
1.667	.171E-26	.0320	2230.425	75	66	7
1.669	.318E-22	.1100	467.787	102	666	3
1.676	.679E-24	.0900	155.389	52	162	1
1.684	.475E-26	.0320	2011.215	75	66	7
1.701	.125E-25	.0320	1803.180	75	66	7
1.703	.212E-22	.1100	579.061	102	666	3
1.718	.310E-25	.0320	1606.353	75	66	7
1.734	.575E-22	.1100	323.620	102	666	3
1.735	.725E-25	.0320	1420.767	75	66	7
1.753	.160E-24	.0320	1246.452	75	66	7
1.764	.437E-27	.0320	1178.121	75	68	7
1.770	.332E-24	.0320	1083.436	75	66	7
1.773	.621E-27	.0320	1099.777	75	68	7
1.781	.868E-27	.0320	1024.107	75	68	7
1.788	.650E-24	.0320	931.745	75	66	7
1.789	.120E-26	.0320	951.113	75	68	7
1.791	.784E-22	.1100	34.251	102	666	3
1.797	.163E-26	.0320	880.799	75	68	7
1.800	.639E-27	.0380	2339.133	75	66	7
1.806	.120E-23	.0380	791.405	75	66	7
1.806	.218E-26	.0350	813.167	75	68	7
NO OF RECORDS=		40				
1.814	.289E-26	.0380	748.219	75	68	7
1.819	.110E-26	.0350	2211.583	75	66	7
1.823	.376E-26	.0370	685.959	75	68	7
1.824	.207E-23	.0350	662.437	75	66	7
1.831	.483E-26	.0350	626.388	75	68	7
1.839	.177E-26	.0370	2095.301	75	66	7
1.840	.610E-26	.0360	569.509	75	68	7
1.842	.336E-23	.0370	544.863	75	66	7
1.846	.481E-22	.1100	281.833	102	666	3

attenuation due to one particular molecular species (M in the sixth column), or (c) considering the attenuation due to all species except one (-M in the sixth column). The number in the seventh column chooses the caption to go with the atmospheric models described above. Three choices of line profile are currently available: Lorentz, Van Vleck-Weisskopf and Gross (kinetic).[7,8,9] These are denoted by 1,2, or 3 respectively in the fifth column. When the frequency at which the attenuation is being calculated coincides within .0005 cm^{-1} with one of the spectral line frequencies in the data file, the three profiles mentioned have been replaced by a Voigt profile for the particular line for which this is true. In this case the center of the line is assumed to coincide exactly with the frequency at which the attenuation is being calculated and the Voigt profile at line center is used. This was found necessary because the vertical attenuation from a given high altitude out into space is greatly overestimated unless line broadening due to the Doppler effect is included. The Voigt profile includes a combination of collisional and Doppler broadening. The choice of Voigt profile at line center was made because this gives the maximum attenuation of which the line is capable. Any other frequency off line center will give a lower attenuation. The SLAM program currently in use is shown in the Appendix.

TABLE III

EXAMPLE OF CONTROL FILE

INITIAL FREQ.	FINAL FREQ.	FREQ. INTERVAL	BOUND	LINE SHAPE	CON.	ATM. MODEL
2.040	2.040	.001	5.	1	7	6

II. METHODS OF CALCULATION

The atmospheric model directly gives the concentrations in grams per cubic meter for water vapor, C1(N), and for ozone, C3(N), at the altitude represented by the (sequential) integer, N. These mass densities are converted into the number of molecules in a column 1 km long by 1 cm^2 cross-sectional area, denoted by W(1,N) and W(3,N), repectively, by the formulae:*

W(1,N) = C1(N) * 3.346E+21
W(3,N) = C3(N) * 1.2546E+21.

For those molecules, M, which have a constant mixing ratio, AM(M), the quantities W(M,N) are computed by the formula:

W(M,N) = (.724270E+24)*P(N)*AM(M)/T(N).

where the numerical factor is the reciprocal of k, the Boltzmann constant, times a power of 10. P(N) and T(N) are respectively, the pressure in millibars and the temperature in degrees Kelvin, as given by the atmospheric model. M = 5 and 7 correspond to carbon monoxide and oxygen, respectively. The mixing ratio AM(M) represents the part of the atmosphere by volume that consists of the naturally occurring isotopic mixture of constituent M:

AM(5) = .075E-06
AM(7) = .2095

---

* W(M,N) = CM(N)/(10*(Molecular Weight)*(1/12*M ^{12}C)),
M(^{12}C) = mass of carbon-twelve atom.

Next, the population of each quantum state capable of absorbing energy in the spectral region under consideration must be determined. The fractional population is given by the expression

EXP(-E/kT)/Q(T),

the Boltzmann exponential population factor EXP(-E/kT) divided by the partition function Q(T), at the temperature T. In absorption, E is the energy of the lower state; k is Boltzmann's constant. The exponential population factor and the partition function have been evaluated at the standard temperature T0=296K and the results are included in the spectral line data file as a factor of the line strength. The corrections to these factors necessary at temperatures T other than T0 are computed by the program. The exact quantum partition function was evaluated at T0=296K,[4-6] and the temperature correction is approximated by assumimg the temperature dependency to be that of the classical rotational partition function (see e.g., Appendix D of Ref. 5). Thus, linear molecules are assumed to have a rotational function that varies directly as the temperature, and non-linear molecules one that varies as the 3/2-power of the temperature. The vibrational partition function at the standard temperature is included but its temperature dependence[2] is neglected. The quantity necessary to adjust the exponential population factor from temperature T0 to T(N) is

CS1(N) = (T0-T(N))/(T0*T(N)*.6946)

and the quantity necessary to adjust the partition function from T0 to T(N) is given by

CS2(M,N) = T0/T(N)

for linear molecules, and by

CS2(M,N) = (T0/T(N)) ** 1.5

for non-linear molecules.

The stimulated emission at T0 was included in the line strength on the original AFCRL data tape. However, the LBL program listed in Ref. (2) did not include corrections to the stimulated-emission factor at other temperatures. In the present SLAM program this stimulated-emission factor has been divided out of the line strengths in the data file and the SLAM program itself computes the required stimulated-emission factor at the arbitrary temperature T(N). This factor is

1. -EXP(-4.86378E-03*GNU(I)) ,

where GNU(I) is the wavenumber (cm^{-1}) of the spectral line whose contribution to the attenuation we are considering. The final value of the line strength, when multiplied by the exponential population factor and the stimulated emission factor, and then divided by the partition function is therefore:

SS=S(I)*CS2(M,N)*EXP(-EPD(I)*CS1(N))

*(1.-EXP(-4.86378E-03*GNU(I))).

Here S(I) is the line strength as it appears in the data file (DATA 2) and EPD(I) is the energy of the lower state from which the absorption arises. S(I) also includes as a factor the isotopic abundance ratios of molecules such as $O^{16}O^{18}$ which are included in the file.

Next, the line width must be calculated. The data file contains the half-width of the line at half-maximum at the standard temperature T0, and pressure P0 = 1013 millibars. When the linewidth is assumed to be proportional to the pressure, the temperature and pressure dependence of the line

width may be taken into account by calculating the factor:

CA(N)=((T0/T(N))**0.5)*(P(N)/P0).

This factor, which is a first approximation, assumes that all lines of all species have the same temperature dependence as would occur when the collision diameters are independent of temperature. The half-width is therefore given by

ALPHA1 = ALPHA(I)*CA(N).

where ALPHA(I) is the half width at P0,T0 of the Ith line given in the file.

Three line shapes can be chosen by the user for the calculations: the Lorentz, Van Vleck-Weisskopf (VVWF), and "kinetic" (Gross) line shapes. For any line shape, the auxiliary quantitities

Z = V-GNU(I)

Z1=V+GNU(I)

are calculated first, where V is the wavenumber at which the attenuation is to be calculated, and GNU(I) is the wavenumber of the Ith line. If

ABS(Z).LE..0005

the Voigt profile[10] is used for the calculation.

For the Lorentz line shape, the quantity

SUM1(M)=SS*ALPHA1/(Z**2+ALPHA1**2)

is calculated.

The Van Vleck-Weisskopf shape requires first the calculation of

VVWF=(1./(Z**2+ALPHA1**2)) + (1./(Z1**2+ALPHA1**2))

and then the calculation of

SUM1(M)=(SS*ALPHA1*(V**2)/(GNU(I)**2))*VVWF.

The Gross (kinetic) line shape is obtained by first calculating the factor

GR=((Z*Z1)**2)+(4.*(GNU(I)**2)*(ALPHA1**2))

and then calculating

SUM1(M)=SS*ALPHA1*4.*(GNU(I)**2)/GR.

The Doppler broadening is determined by the parameter BETA which is the half-width divided by $\sqrt{\ln 2}$ of the Doppler broadened line at half-maximum. The quantities DOP(M) which depend on the masses of the individual molecular species M are stored in the program as DATA and are used to compute:

DOP1(N1,N2)=DOP(N1)*T(N2)**.5

which now depends on the altitude and atmospheric model through dependence on the temperature T(N2). Then BETA is given by:

BETA=GNU(I)*DOP1(M,N)

where the dependence on the line frequency is now included. The shape of the Voigt profile depends on the dimensionless variable Y:

Y=ALPHA1/BETA,

which is the ratio of the Lorentz half-width to the Doppler parameter.

In the special case of the center of a line, calculation of the Voigt profile can be reduced to the calculation of the probability integral. When GNU(I)=30 cm^{-1} and Z=.001 cm^{-1} the parameters are already such that the Voigt profile can be approximated by a Lorentz shape. Therefore in the first approximation it was not thought necessary to replace the other profiles by a Voigt one except possibly for the line nearest the frequency at which the attenuation is being calculated. The expression to be evaluated is:

$$\frac{2}{BETA}\, e^{Y^2} \int_Y^{\infty} e^{-q^2}\, dq$$

where a factor $1/\pi$ has been omitted.

When (Y.GE.5.) the asymptotic formula for the probability integral is used, giving:

```
SUM1(M)=SS*(1./Y-.5/Y3+.75/Y5
          -1.875/Y7+6.5625/Y9)/BETA
```

where Y3 is the third power of Y, etc. When Y is less than 5 an approximation of Hastings[11] is used. Let:

```
TY=1./(1.+.3275911*Y)
```

and TY3 be the third power of TY, etc. Then use of Hastings' approximation gives:

```
SUM1(M)=SS*1.772454*(.2548296*TY
  -.2844967*TY2+1.421414*TY3-1.453152*TY4
  +1.061405*TY5)/BETA.
```

All line shapes given above neglect a possible shift of resonant frequency with pressure of about .01 cm^{-1} per atmosphere.[12] This sets a limit on the precision with which it is desirable to give the resonant wavenumbers in the data file. (Note that .001 cm^{-1}=30 MHz, a reasonable modulation bandwidth.) In addition, the exact shape of the spectral lines far from the resonant frequencies is not settled, especially for the case of water vapor. In this case, besides the usual monomer form, water dimers may exist and contribute appreciably to the absorption.

Currently, the continuum contributions (due primarily to N_2 and in part to non-resonant absorption by O_2) have not yet been included in the SLAM program. Thus, the attenuation in the vicinity of absorption minima will be somewhat underestimated.

To determine the attenuation, the quantities SUM1(M) from the different lines of the species M must be added at a fixed wavenumber:

```
CAY1(M)=CAY1(M)+SUM1(M),
```

where this sum is iterated over all the relevant lines.

The quantity CAY1(M) is next multiplied by W(M,N) and the result summed over M:

CAY=CAY+CAY1(M)*W(M,N).

Finally, a normalization factor of $1/\pi$ omitted in the definition of the lineshape, and conversion of units into dB/km, gives the formula

OPD(IV)=CAY*1.38246

where OPD is the horizontal attenuation in dB/km.

In addition to the horizontal attenuations at the levels represented by N, the integrated attenuations from these levels down to the ground and up into space are calculated. The integration is performed by means of the trapezoidal rule. An iteration of the formula

SUM=SUM+.5*(H(N)-H(N-1))*(OPD(IV)+SAVE)

gives the attenuation from the height H(N) down to the ground level, where OPD(IV) is the horizontal attenuation at H(N), SAVE is the horizontal attenuation at the height H(N-1) and SUM is initialized to zero at the ground level. Then

DOWN(N,IV)=SUM

is the attenuation in dB from the level H(N) down to the ground,

HOR(N,IV)=OPD(IV)

is the horizontal attenuation in dB/km, while

UP(N,IV)=SUM-DOWN(N,IV)

is the attenuation in dB from the height H(N) out into space. In the latter formula SUM represents the attenuation from the highest level down to the ground. The wavenumber is then incremented and the calculation begun anew.

III. SLAM OUTPUT FORMATS

Typical output in tabular form is shown in Tables IV and V. Columns labeled HEIGHT give the altitude in kilometers above mean sea level, those marked HOR give the attenuation in the horizontal direction in dB/km, those marked DOWN give the total attenuation in dB from the height indicated down to sea level, while those marked UP give the total attenuation in dB from the height indicated vertically outwards into space. The numbers marked FREQUENCY give the frequency (in cm^{-1}) at which the calculations were done. From the heading, we note that a Van Vleck-Weisskopf line profile was used in Table IV, that BOUND was 20 cm^{-1}, that all constituents on the data file were used in the calculation (shown by the value 0 after CONSTITUENT), and that the U.S. Standard Atmosphere, 1962 was used. This frequency is in a valley between two water vapor absorption lines. Table V shows the results of a calculation identical to that of Table IV, except that a Gross profile was used instead of the Van Vleck-Weisskopf profile. The two results for HOR differ by about 25% at sea level, but the difference grows considerably larger at high altitudes. At the peak of absorption lines little difference is found in the calculated attenuation as a function of line shape.

Figures 1 through 7 show typical graphical output. Figures 1 and 2 present graphs of HOR, DOWN and UP corresponding to the numerical output of Tables IV and V. The caption identifies the various curves and shows whether they are measured in dB or dB/km, i.e., whether the scale of ordinates on the left or on the right is to be used. The abscissa is the HEIGHT, and the caption gives information similar to that in the tabular output,

TABLE IV

SLAM Output for 7.200 and 7.300 cm^{-1} with Van Vleck - Weisskopf Profile

```
0032:    DK,00306314     01/23/76     15:59
V1=      7.200V2=     7.300DV=      .100BOUNU=      20.000  U.S. STANDARD ATM.,1962
VBOT      -12.800VTOP       27.300GNU(1)=      .307GNU=       27.32811      676
   2     7.3000     7.3280   VAN VLECK-WEISSKOPF PROFILE    CONSTITUENT=      0
```

FREQUENCY= 7.200

HEIGHT	HOR	DOWN	UP	HEIGHT	HOR	DOWN	UP
.000	.59063E 00	.00000E 00	.13130E 01	1.000	.39202E 00	.49132E 00	.82167E 00
2.000	.25334E 00	.81400E 00	.49900E 00	3.000	.14937E 00	.10154E 01	.29764E 00
4.000	.87964E-01	.11340E 01	.17898E 00	5.000	.50712E-01	.12034E 01	.10964E 00
6.000	.30472E-01	.12439E 01	.69046E-01	7.000	.18083E-01	.12682E 01	.44769E-01
8.000	.11417E-01	.12830E 01	.30020E-01	9.000	.66141E-02	.12920E 01	.21005E-01
10.000	.43804E-02	.12975E 01	.15508E-01	11.000	.31955E-02	.13013E 01	.11721E-01
12.000	.23081E-02	.13040E 01	.89693E-02	13.000	.16978E-02	.13060E 01	.69666E-02
14.000	.12755E-02	.13075E 01	.54808E-02	15.000	.97816E-03	.13086E 01	.43545E-02
16.000	.75744E-03	.13095E 01	.34876E-02	17.000	.61226E-03	.13102E 01	.28028E-02
18.000	.49706E-03	.13107E 01	.22488E-02	19.000	.40477E-03	.13112E 01	.17986E-02
20.000	.33336E-03	.13116E 01	.14305E-02	21.000	.26492E-03	.13119E 01	.11320E-02
22.000	.21504E-03	.13121E 01	.89264E-03	23.000	.17060E-03	.13123E 01	.70000E-03
24.000	.13349E-03	.13124E 01	.54836E-03	25.000	.10455E-03	.13126E 01	.43011E-03
30.000	.26323E-04	.13129E 01	.10300E-03	35.000	.62922E-05	.13130E 01	.21935E-04
40.000	.13308E-05	.13130E 01	.38147E-05	45.000	.25284E-06	.13130E 01	.00000E 00
50.000	.44750E-07	.13130E 01	.00000E 00	70.000	.20129E-09	.13130E 01	.00000E 00
100.000	.53203E-14	.13130E 01	.00000E 00				

FREQUENCY= 7.300

HEIGHT	HOR	DOWN	UP	HEIGHT	HOR	DOWN	UP
.000	.57146E 00	.00000E 00	.12710E 01	1.000	.37954E 00	.47550E 00	.79547E 00
2.000	.24547E 00	.78800E 00	.48297E 00	3.000	.14491E 00	.98319E 00	.28778E 00
4.000	.85464E-01	.10984E 01	.17259E 00	5.000	.49366E-01	.11658E 01	.10518E 00
6.000	.29722E-01	.12053E 01	.65634E-01	7.000	.17676E-01	.12290E 01	.41935E-01
8.000	.11177E-01	.12435E 01	.27509E-01	9.000	.64750E-02	.12523E 01	.18683E-01
10.000	.42671E-02	.12577E 01	.13313E-01	11.000	.30645E-02	.12613E 01	.96483E-02
12.000	.21637E-02	.12639E 01	.70343E-02	13.000	.15554E-02	.12658E 01	.51756E-02
14.000	.11294E-02	.12671E 01	.38338E-02	15.000	.83117E-03	.12681E 01	.28543E-02
16.000	.61271E-03	.12688E 01	.21324E-02	17.000	.45593E-03	.12694E 01	.15984E-02
18.000	.33968E-03	.12698E 01	.12007E-02	19.000	.25415E-03	.12701E 01	.90408E-03
20.000	.19108E-03	.12703E 01	.68188E-03	21.000	.14[illegible]26E-03	.12705E 01	.51594E-03
22.000	.10686E-03	.12706E 01	.39196E-03	23.000	.80150E-04	.12707E 01	.29850E-03
24.000	.60049E-04	.12707E 01	.22888E-03	25.000	.45169E-04	.12708E 01	.17643E-03
30.000	.10238E-04	.12709E 01	.38147E-04	35.000	.22726E-05	.12710E 01	.76294E-05
40.000	.50123E-06	.12710E 01	.99367E-06	45.000	.11372E-06	.12710E 01	.00000E 00
50.000	.27705E-07	.12710E 01	.00000E 00	70.000	.16704E-09	.12710E 01	.00000E 00
100.000	.51881E-14	.12710E 01	.00000E 00				

TABLE V

SLAM Output for 7.200 and 7.300 cm^{-1} with Gross Profile

```
V1=      7.200V2=      7.300DV=       .100BOUND=     20.000  U.S. STANDARD ATM.,1962
VBOT       -12.800VTOP        27.300GNU(1)=          .307GNU=       27.328I1     676
   2     7.3000      7.3280   GROSS PROFILE   CONSTITUENT=     0
```

FREQUENCY= 7.200

HEIGHT	HOR	DOWN	UP	HEIGHT	HOR	DOWN	UP
.000	.73564E 00	.00000E 00	.15470E 01	1.000	.48283E 00	.60923E 00	.93772E 00
2.000	.30701E 00	.10042E 01	.54280E 00	3.000	.17540E 00	.12454E 01	.30159E 00
4.000	.98741E-01	.13824E 01	.16452E 00	5.000	.53066E-01	.14583E 01	.88618E-01
6.000	.29180E-01	.14995E 01	.47496E-01	7.000	.15108E-01	.15216E 01	.25352E-01
8.000	.81696E-02	.15332E 01	.13715E-01	9.000	.33039E-02	.15390E 01	.79784E-02
10.000	.15540E-02	.15414E 01	.55504E-02	11.000	.94570E-03	.15427E 01	.43011E-02
12.000	.63069E-03	.15434E 01	.35133E-02	13.000	.46134E-03	.15440E 01	.29678E-02
14.000	.36737E-03	.15444E 01	.25539E-02	15.000	.31478E-03	.15447E 01	.22135E-02
16.000	.27276E-03	.15450E 01	.19197E-02	17.000	.25777E-03	.15453E 01	.16546E-02
18.000	.23793E-03	.15455E 01	.14076E-02	19.000	.21553E-03	.15458E 01	.11816E-02
20.000	.19514E-03	.15460E 01	.97656E-03	21.000	.16473E-03	.15462E 01	.79727E-03
22.000	.14236E-03	.15463E 01	.64373E-03	23.000	.11782E-03	.15464E 01	.51403E-03
24.000	.55133E-04	.15465E 01	.40817E-03	25.000	.76691E-04	.15466E 01	.32234E-03
30.000	.20415E-04	.15469E 01	.80109E-04	35.000	.50126E-05	.15469E 01	.17166E-04
40.000	.10372E-05	.15470E 01	.28610E-05	45.000	.17998E-06	.15470E 01	.00000E 00
50.000	.24559E-07	.15470E 01	.00000E 00	70.000	.65996E-10	.15470E 01	.00000E 00
100.000	.10154E-14	.15470E 01	.00000E 00				

FREQUENCY= 7.300

HEIGHT	HOR	DOWN	UP	HEIGHT	HOR	DOWN	UP
.000	.72656E 00	.00000E 00	.15261E 01	1.000	.47698E 00	.60177E 00	.92435E 00
2.000	.30336E 00	.99194E 00	.53418E 00	3.000	.17334E 00	.12303E 01	.29583E 00
4.000	.97594E-01	.13658E 01	.16037E 00	5.000	.52446E-01	.14408E 01	.85345E-01
6.000	.28829E-01	.14814E 01	.44708E-01	7.000	.14908E-01	.15033E 01	.22840E-01
8.000	.80407E-02	.15148E 01	.11366E-01	9.000	.32094E-02	.15204E 01	.57411E-02
10.000	.14612E-02	.15227E 01	.34065E-02	11.000	.82660E-03	.15239E 01	.22631E-02
12.000	.49362E-03	.15245E 01	.16031E-02	13.000	.32390E-03	.15249E 01	.11950E-02
14.000	.22483E-03	.15252E 01	.92125E-03	15.000	.17060E-03	.15254E 01	.72384E-03
16.000	.13027E-03	.15255E 01	.57411E-03	17.000	.10332E-03	.15257E 01	.45776E-03
18.000	.82132E-04	.15258E 01	.36526E-03	19.000	.66237E-04	.15258E 01	.29182E-03
20.000	.53992E-04	.15259E 01	.23174E-03	21.000	.42990E-04	.15259E 01	.18406E-03
22.000	.34945E-04	.15260E 01	.14591E-03	23.000	.27994E-04	.15260E 01	.11539E-03
24.000	.22193E-04	.15260E 01	.90599E-04	25.000	.17706E-04	.15260E 01	.71526E-04
30.000	.44326E-05	.15261E 01	.16212E-04	35.000	.10174E-05	.15261E 01	.28610E-05
40.000	.21271E-06	.15261E 01	.00000E 00	45.000	.41794E-07	.15261E 01	.00000E 00
50.000	.76633E-08	.15261E 01	.00000E 00	70.000	.32278E-10	.15261E 01	.00000E 00
100.000	.89594E-15	.15261E 01	.00000E 00				

concerning the choice of parameters for the calculation. Comparison of Fig. 1 and 2 again shows the effect of line shape.

Figures 3 and 4 plot the computed attenuation for a frequency of 2.040 cm^{-1}, which is at the peak of the 60 GHz oxygen microwave absorption band. Figure 3 shows the attenuation computed as described above with the Voigt profile substituted for the Lorentz profile for the nearest line. In Figure 4 the Lorentz profile at the center of a line has been used for this line too. Corresponding numerical values are shown in Tables VI and VII. It can be seen that HOR begins to differ appreciably for the two cases above 50 km. This lends to a considerable difference in the computed value of UP at all altitudes. Although the Lorentz line shape was used for this calculation in order to facilitate comparison with the work of Liebe and Welch,[13] the Van Vleck-Weisskopf profile is generally considered more accurate in the microwave region and the Gross profile is perferred in the submillimeter region. Comparison of Fig. 3 with Fig. 1 or 2 shows considerable difference in the shape of the altitude-dependent curves. The relatively fast drop-off of the HOR curve in Figs. 1 and 2 is undoubtedly due to the small scale-height for water vapor, which contributes most of the absorption in the troughs. The scale-height for oxygen, however, is the same as that of the atmosphere as a whole, so that HOR at the peak of an oxygen absorption line does not fall off as rapidly.

Figures 5, 6, and 7 are calculated at a frequency of 14.169 cm^{-1}, which is the peak of one of the strong molecular oxygen submillimeter lines. Figure 5 is calculated with all the constituents in the data file (CONSTITUENT =0), Fig. 6 with only the oxygen lines (CONSTITUENT =7), and Fig. 7 with all lines except those of oxygen (CONSTITUENT =-7). Otherwise, the calculations for these figures were done using identical

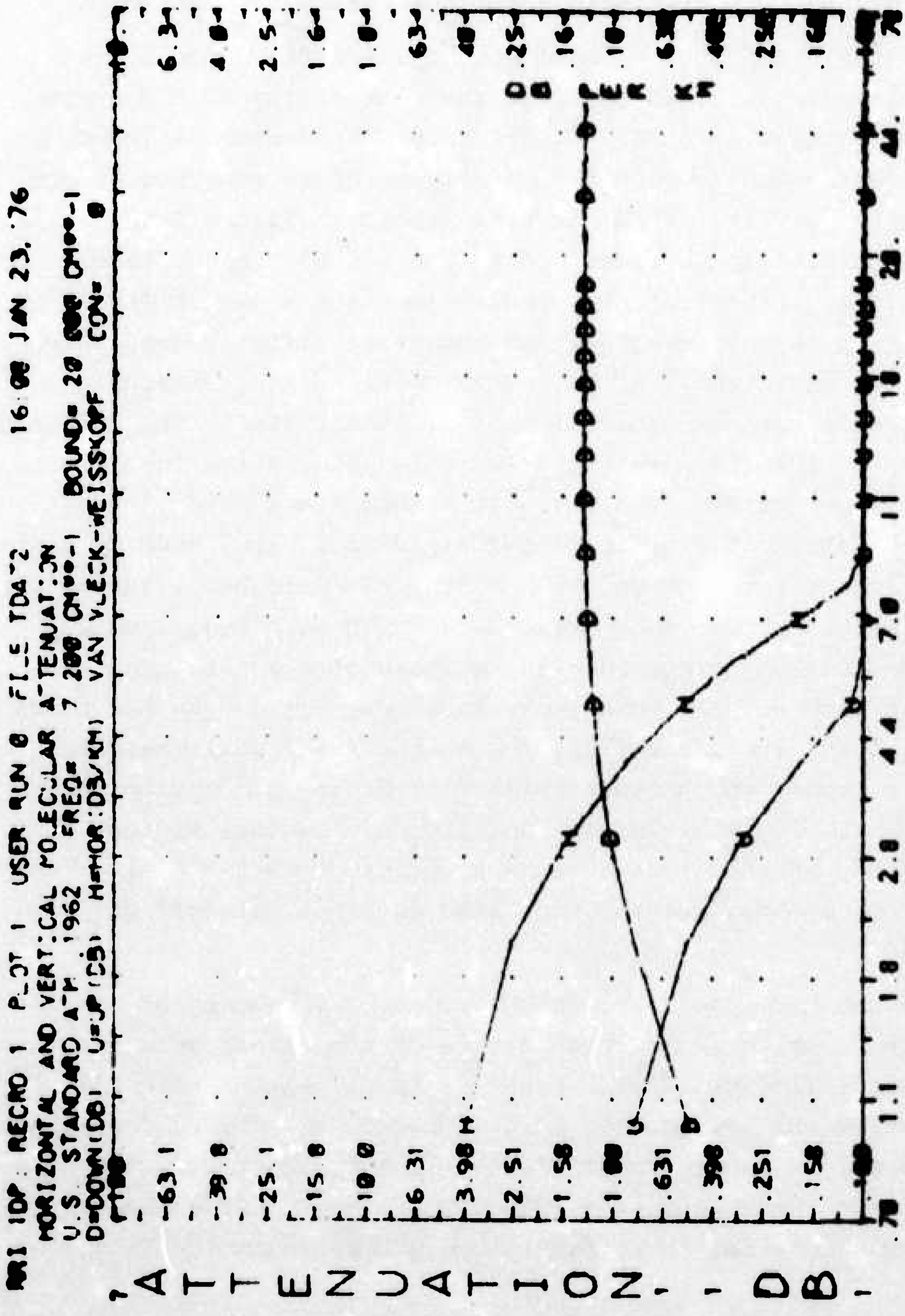

FIG. 1: SLAM Output for 7.200 cm^{-1} with Van Vleck-Weisskopf Profile.

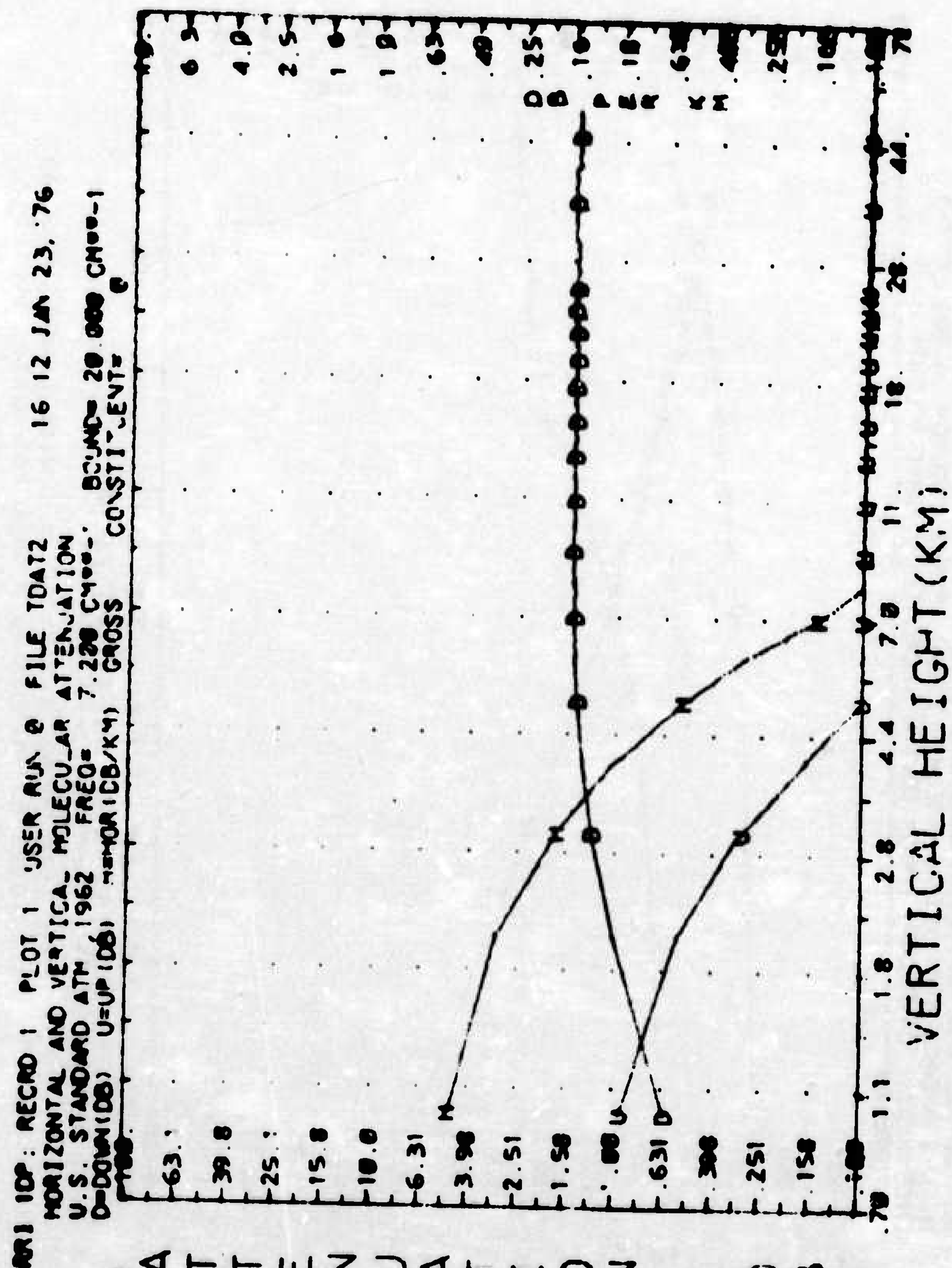

FIG. 2: SLAM Output for 7.200 cm^{-1} with Gross Profile.

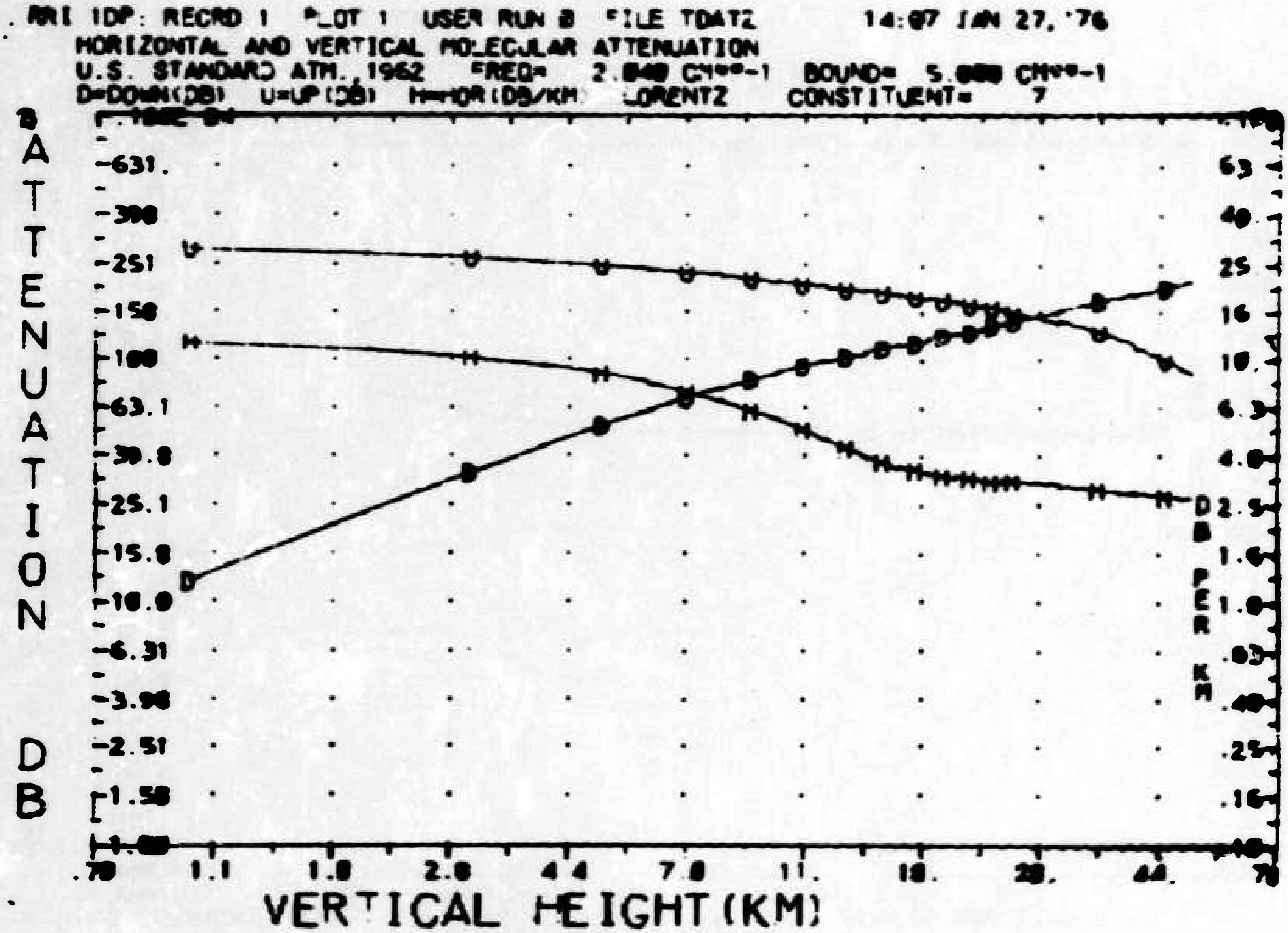

FIG. 3: SLAM Output for 2.040 cm^{-1} with Lorentz Profile used for all lines except the center line for which the Voigt Profile is used.

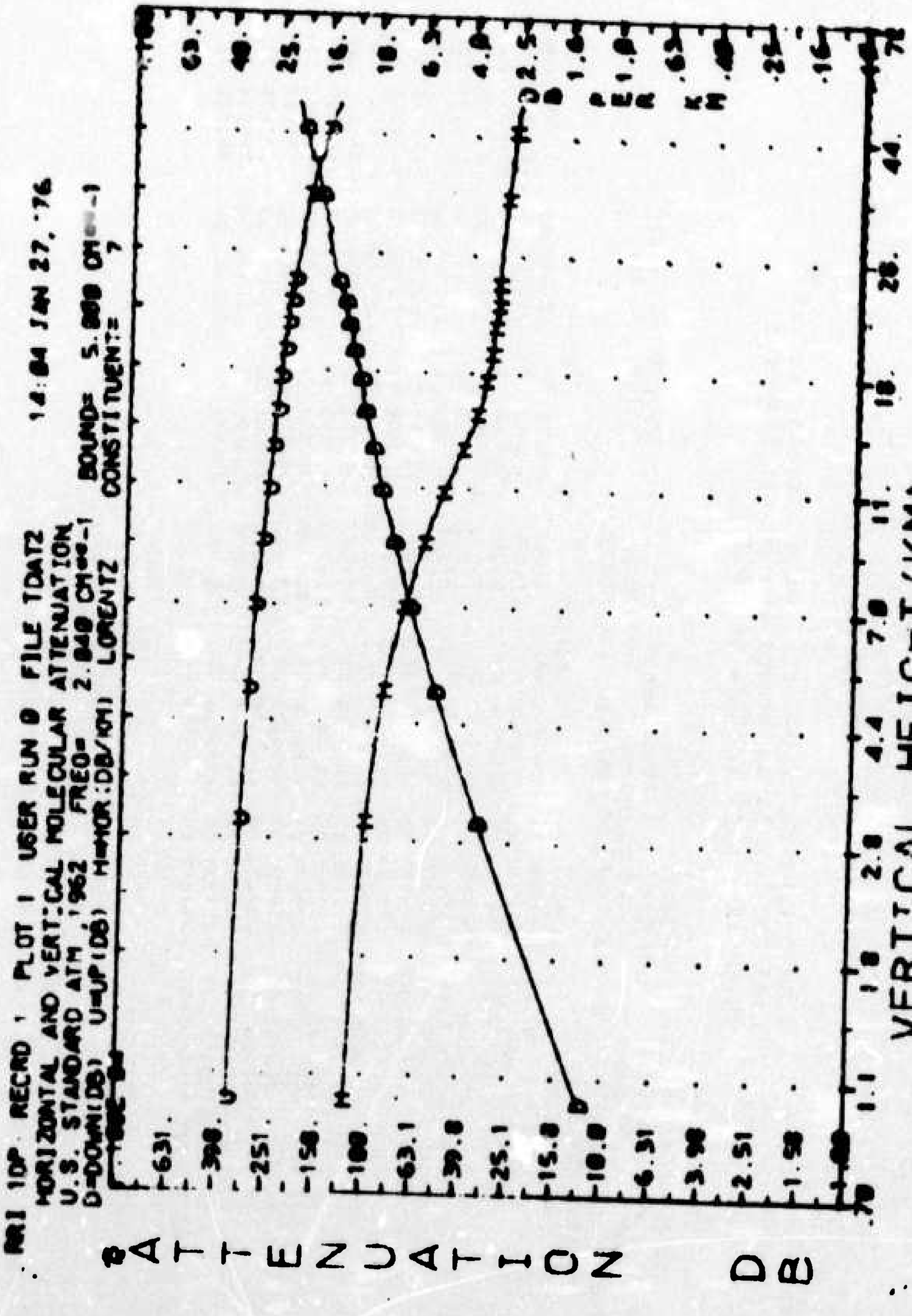

FIG. 4: SLAM Output for 2.040 cm^{-1} with Lorentz Profile used for all lines.

TABLE VI

SLAM Output for 2.040 cm^{-1} with Lorentz Profile used for all lines except the center line for which the Voigt Profile is used.

```
001C:    DK,003C6314     01/26/76    11:23
V1=      2.040V2=      2.040DV=      .100BOUND=      5.000  U.S. STANDARD ATM.,1962
VBOT       -2.960VTOP        7.040GNU(1)=        .307GNU=        7.170I1      227
   1     2.0400     2.1700    LORENTZ PROFILE    CONSTITUENT=     7
FREQUENCY=      2.040
```

HEIGHT	HOR	DOWN	UP	HEIGHT	HOR	DOWN	UP
.000	.12442E 02	.00000E 00	.29984E 03	1.000	.11675E 02	.12058E 02	.28778E 03
2.000	.10903E 02	.23348E 02	.27649E 03	3.000	.10128E 02	.33863E 02	.26598E 03
4.000	.93650E 01	.43609E 02	.25623E 03	5.000	.86204E 01	.52602E 02	.24724E 03
6.000	.79036E 01	.60864E 02	.23898E 03	7.000	.72265E 01	.68429E 02	.23141E 03
8.000	.65983E 01	.75341E 02	.22450E 03	9.000	.60314E 01	.81656E 02	.21819E 03
10.000	.55315E 01	.87438E 02	.21240E 03	11.000	.50998E 01	.92753E 02	.20709E 03
12.000	.46142E 01	.97610E 02	.20223E 03	13.000	.42331E 01	.10203E 03	.19781E 03
14.000	.39412E 01	.10612E 03	.19372E 03	15.000	.37202E 01	.10595E 03	.18989E 03
16.000	.35542E 01	.11359E 03	.18625E 03	17.000	.34308E 01	.11708E 03	.18276E 03
18.000	.33390E 01	.12047E 03	.17938E 03	19.000	.32711E 01	.12377E 03	.17607E 03
20.000	.32209E 01	.12702E 03	.17282E 03	21.000	.31740E 01	.13021E 03	.16963E 03
22.000	.31373E 01	.13337E 03	.16647E 03	23.000	.31080E 01	.13649E 03	.16335E 03
24.000	.30840E 01	.13959E 03	.16025E 03	25.000	.30640E 01	.14266E 03	.15718E 03
30.000	.29953E 01	.15781E 03	.14203E 03	35.000	.29005E 01	.17255E 03	.12729E 03
40.000	.27789E 01	.18675E 03	.11309E 03	45.000	.26629E 01	.20035E 03	.99488E 02
50.000	.26062E 01	.21353E 03	.86315E 02	70.000	.23893E 01	.26348E 03	.36360E 02
100.000	.34665E-01	.29984E 03	.00000E 00				

TABLE VII

SLAM Output for 2.040 cm^{-1} with Lorentz Profile used for all lines.

```
V1=      2.040V2=      2.040DV=      .100BOUND=      5.000  U.S. STANDARD ATM.,1962
VBOT        =2.960VTOP        7.040GNU(1)=        .307GNU=        7.170I1      227
    1    2.0400      2.17C0    LORENTZ PROFILE    CONSTITUENT=     7
FREQUENCY=     2.040
```

HEIGHT	HOR	DOWN	UP	HEIGHT	HOR	DOWN	UP
.000	.12442E 02	.00000E 00	.36304E 03	1.000	.11675E 02	.12058E 02	.35098E 03
2.000	.10903E 02	.[illegible]348E 02	.33970E 03	3.000	.10128E 02	.33863E 02	.32918E 03
4.000	.93650E 01	.43609E 02	.31943E 03	5.000	.86204E 01	.52602E 02	.31044E 03
6.000	.79036E 01	.60864E 02	.30218E 03	7.000	.72265E 01	.68429E 02	.29461E 03
8.000	.65983E 01	.75341E 02	.28770E 03	9.000	.60314E 01	.81656E 02	.28139E 03
10.000	.55315E 01	.87438E 02	.27561E 03	11.000	.50998E 01	.92753E 02	.27029E 03
12.000	.46142E 01	.97610E 02	.26543E 03	13.000	.42331E 01	.10203E 03	.26101E 03
14.000	.39413E 01	.10612E 03	.25692E 03	15.000	.37202E 01	.10995E 03	.25309E 03
16.000	.35543E 01	.11359E 03	.24945E 03	17.000	.34308E 01	.11708E 03	.24596E 03
18.000	.33390E 01	.12047E 03	.24258E 03	19.000	.32711E 01	.12377E 03	.23927E 03
20.000	.32209E 01	.12702E 03	.23603E 03	21.000	.31740E 01	.13021E 03	.23283E 03
22.000	.31373E 01	.13337E 03	.22967E 03	23.000	.31080E 01	.13649E 03	.22655E 03
24.000	.30840E 01	.13959E 03	.22345E 03	25.000	.30640E 01	.14266E 03	.22038E 03
30.000	.29953E 01	.15781E 03	.20523E 03	35.000	.29007E 01	.17255E 03	.19049E 03
40.000	.27794E 01	.18675E 03	.17629E 03	45.000	.26651E 01	.20036E 03	.16268E 03
50.000	.26140E 01	.21356E 03	.14948E 03	70.000	.30501E 01	.27020E 03	.92842E 02
100.000	.31394E 01	.36304E 03	.00000E 00				

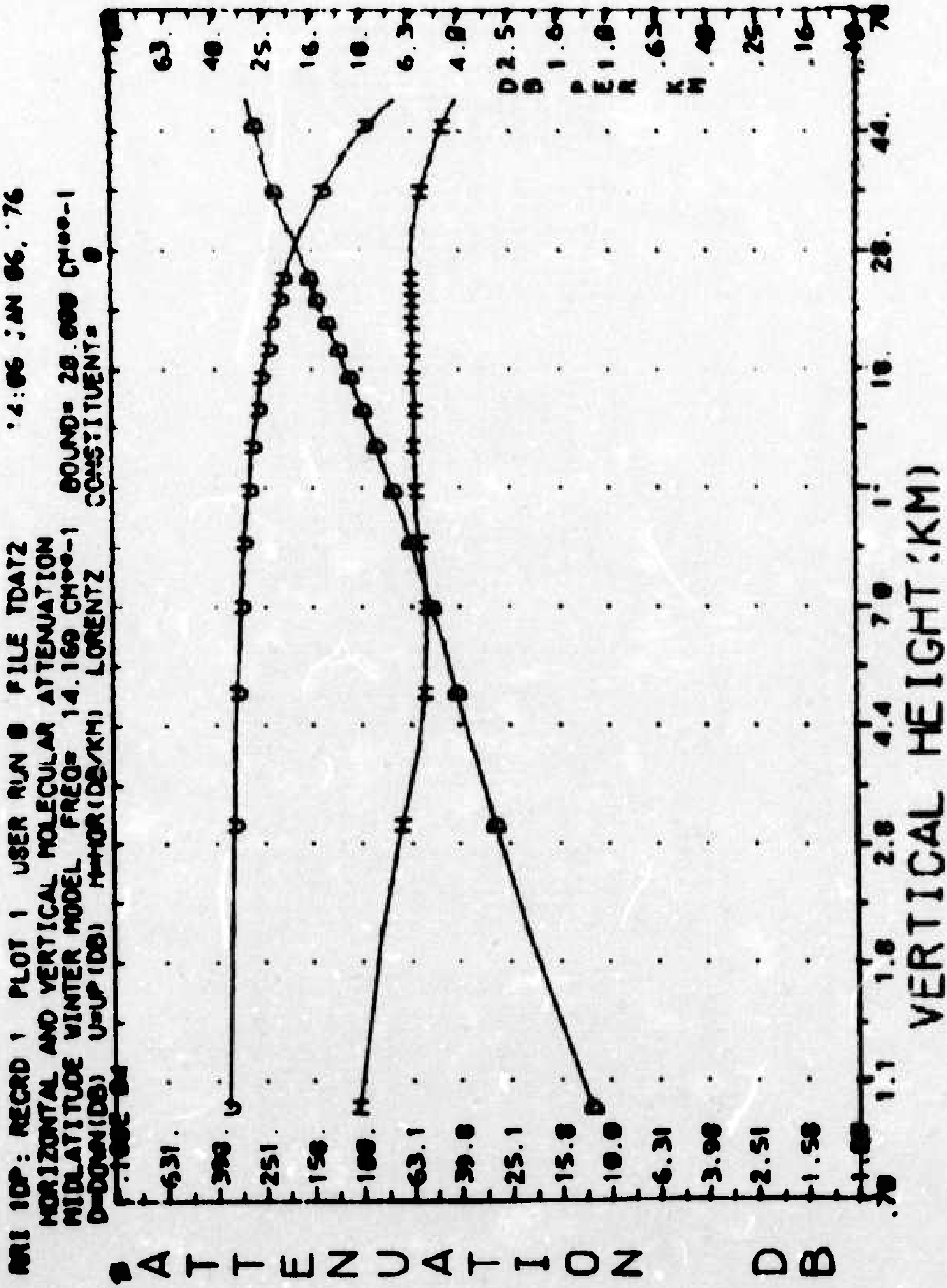

FIG. 5: SLAM Output for 14.169 cm^{-1} with all constituents present.

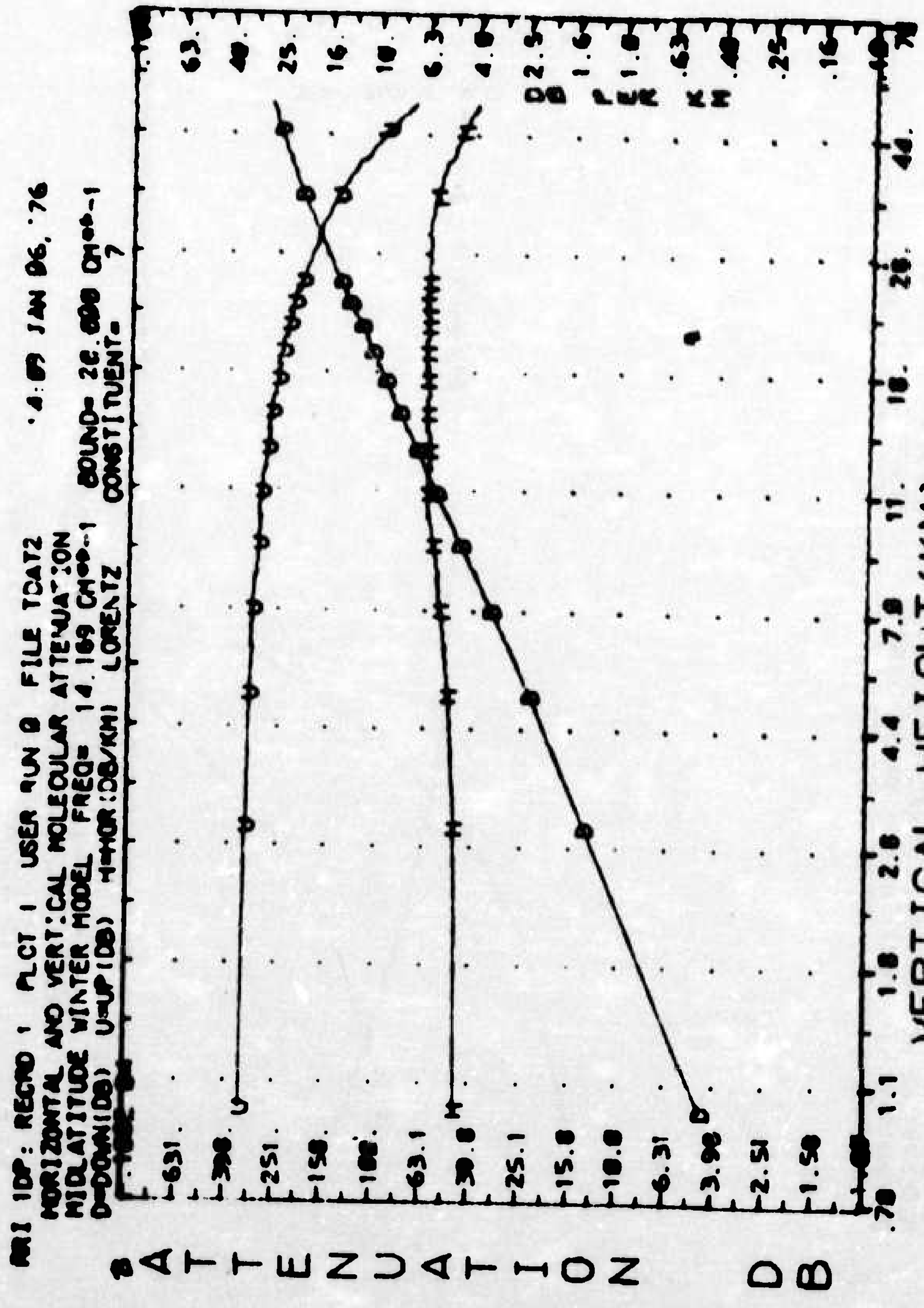

FIG. 6: SLAM Output for 14.169 cm^{-1} with only oxygen present.

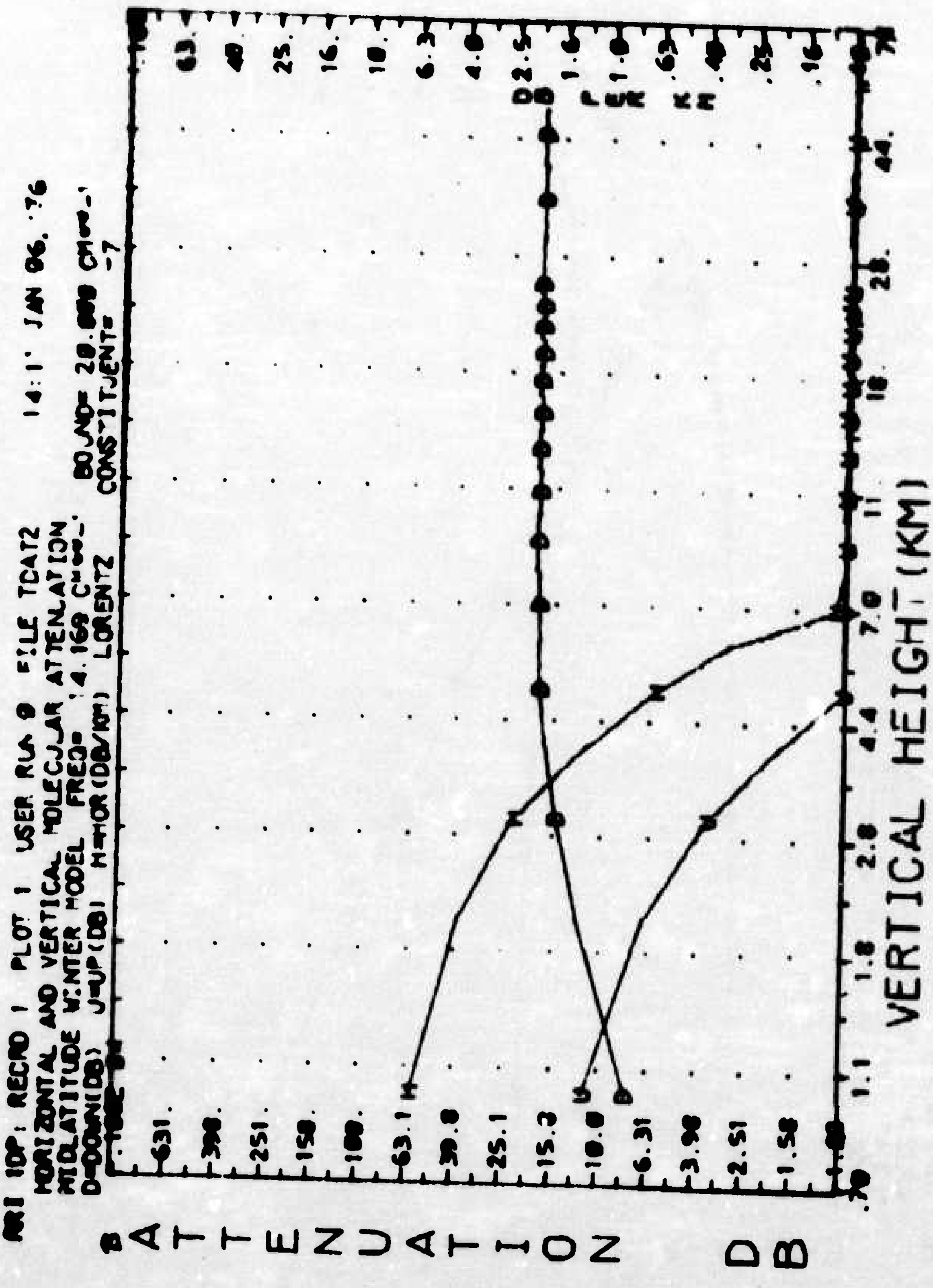

FIG. 7: SLAM Output for 14.169 cm^{-1} with all constituents except oxygen present.

values of the parameters. Comparison of Figs. 5 and 6 shows that the general altitude-dependence of the attenuation can be traced to the oxygen. Figure 7 shows that the other constituents make an appreciable contribution at low altitudes. Thus, the importance of including the oxygen submillimeter spectrum in this spectral region is illustrated.

IV. COMPARISON WITH CALCULATIONS BY OTHERS

Table VIII shows the results of varying BOUND within the SLAM program for a frequency of 1.000 cm^{-1}. Also shown are a comparison with calculations by Van Vleck.[14] In these calculations only lines in the spectrum of water vapor are taken into account, all line half-widths are put equal to .1 cm^{-1} and the temperature and pressure shown in the table are used instead of one of the standard atmospheric models. This was done to make a closer comparison with Van Vleck's results. The quantity given in the table is the horizontal attenuation in dB/km per unit density of water vapor, the latter expressed in g/m^3. The results agree to about 3.6% which is considered satisfactory.

Table IX shows a comparison of the results of calculations performed by SLAM with those performed at AFCRL[4]. The results of varying BOUND within the SLAM program for this higher frequency are also shown. The discrepency between the SLAM and AFCRL calculations is about ten percent. This is considered a reasonable agreement; further comments are difficult to make since full documentation concerning the AFCRL calculations are not available at RRI.

Table X compares the results of SLAM and those of Liebe and Welch[13], using the Lorentz profile and U.S. Standard Atmosphere, 1962 used by those investigators. The quantities BOUND and CONSTITUENT are set so that only the oxygen microwave spectrum contributes to the attenuation. The discrepancy between the two calculations ranges up to a factor of two at 10 km. It is believed that this discrepancy can be traced to different assumptions made concerning the variation of line half-width

FREQUENCY = 1.000 cm^{-1} VAN VLECK - WEISSKOPF PROFILE CONSTITUENT = 1

LINE HALF-WIDTH = .1 cm^{-1}

TEMPERATURE = 293 K PRESSURE = 1013 mb

BOUND (cm^{-1})	0.45	20.	40.	60.	80.	100.	120.	140.
HOR $\left(\frac{db/km}{g/m^3}\right)$	0.00487	0.00541	0.00575	0.00589	0.00595	0.00602	0.00603	0.00603

DEPENDENCE OF SLAM PREDICTIONS ON BOUND

	1.35 cm^{-1} line	RESIDUAL	TOTAL
SLAM $\left(\frac{db/km}{g/m^3}\right)$	0.00487	0.00116	0.00603
VAN VLECK $\left(\frac{db/km}{g/m^3}\right)$	0.0047	0.00116	0.00586

COMPARISON BETWEEN SLAM PREDICTIONS AND VAN VLECK[14] PREDICTIONS

TABLE VIII

FREQUENCY = 29.713 cm^{-1} VAN VLECK-WEISSKOPF PROFILE MIDLATITUDE WINTER MODEL

CONSTITUENT = 0

HEIGHT (km)	SLAM (dB/km)				AFCRL (dB/km)
BOUND(cm^{-1}) =	20	50	75	100	100
0 *	23.64	24.94	25.26	25.28	27.4
9-10 **	0.032	0.037	0.037	0.037	0.041

* HORIZONTAL ATTENUATION

** ATTENUATION BETWEEN THE GIVEN LEVELS

COMPARISON OF SLAM RESULTS WITH AFCRL RESULTS[4]

TABLE IX

FREQUENCY = 2.040 cm^{-1}

LORENTZ PROFILE

U.S. STANDARD ATMOSPHERE (1962)

BOUND = 5

CONSTITUENT = 7

HEIGHT (km)	HORIZONTAL ATTENUATION (SLAM) (dB/km)	HORIZONTAL ATTENUATION (LIEBE AND WELCH[13]) (dB/km)
0	12.45	14.4
10	5.55	10.85
20	3.20	5.4
30	2.51	2.75

COMPARISON BETWEEN SLAM AND LIEBE AND WELCH

TABLE $\overline{X}$

with altitude. The SLAM program assumes line half-widths characteristic of well separated, isolated lines, which is justified for low pressures of the broadening gas. However, due to interaction between overlapping lines, at higher pressures the attenuation far from the oxygen band is overestimated by this procedure. An empirical correction is often made by decreasing the assumed line half-widths until the calculated attenuation outside the band matches the observed result. In the calculations of Liebe and Welch[13] this empirically corrected line half-width has been used up to an altitude of about 15 km after which a gradual transition to the line half-widths characteristic of the isolated lines is made. Since at 10 km the overlapping of the lines has decreased considerably this could account for the large discrepancy between the two calculations at that altitude.

V. COMPARISON WITH EXPERIMENTS

Table XI shows a comparison of SLAM output with experimental results of Becker and Autler[15] and of Burroughs, Jones and Gebbie[16]. Only attenuation by water vapor is included and the results are normalized to 1 g/m^3 of water vapor. Again, instead of one of the standard atmospheric models, the temperature and pressures shown, appropriate for a comparison with the corresponding experiment, have been used. There is substantial agreement between experiment and the results of either the Van Vleck-Weisskopf or Gross profiles at .784 cm^{-1}, which is near the 22 GHz water vapor absorption line. Further from this line the discrepancy increases to a factor of about 50% at 1.160 cm^{-1} and 100% at 1.340 cm^{-1}. The Lorentz profile results are considerably more discordant. The values quoted from Burroughs, Jones and Gebbie[16] have been obtained by evaluating their least squares fitted polynomial, which is a function of the broadener pressure, at the appropriate value of the atmospheric pressure. In this evaluation the term independent of the broadener pressure has been omitted as being due to the broadening of the water vapor lines by water vapor, which is not included in the SLAM program. It can be seen that the experimentally determined attenuations are still considerably higher than the calculated ones.

Table XII compares the SLAM output with atmospheric observations by Lo, Fannin and Straiton[17]. These numbers have been taken from one of their fitted curves. Also shown are the decomposition of the calculated absorption into the sum of absorption by oxygen and by water vapor. From the above discussions it follows that two compensating errors are present in these

CONSTITUENT = 1   BOUND = 100 cm^{-1} PRESSURE = 1 ATM

FREQUENCY (cm^{-1})	TEMPERATURE (^{0}K)	LORENTZ	HOR $\frac{dk/km}{g/m^3}$ VAN VLECK WEISSKOPF	GROSS	EXPERIMENT
0.784	318	0.8498	0.0240	0.0224	0.0230[15]
1.160	318	0.8438	0.00371	0.00406	0.0067[15]
1.340	318	0.8502	0.00345	0.00441	0.0086[15]
29.713	293	9.00	6.54	7.03	11.5[16]
32.166	293	42.77	38.58	39.9	48.2[16]

COMPARISON OF SLAM OUTPUT WITH SOME EXPERIMENTS

TABLE XI

U.S. STANDARD ATM., 1962 BOUND = $100 cm^{-1}$

FREQUENCY (cm^{-1})	CON	UP (dB) LORENTZ PROFILE	VV-W PROFILE	GROSS PROFILE	OBSERVATIONS
1.167	1	11.48	0.0456	0.0538	
1.167	7	0.359	0.132	0.196	
1.167	0	11.84	0.18	0.25	0.16[17]
3.160	1	12.71	0.167	0.306	
3.160	7	0.210	0.488	0.292	
3.160	0	12.92	0.66	0.598	0.52[17]

COMPARISON OF SLAM OUTPUT WITH SOME OBSERVATIONS

TABLE XII

calculations. The excess attenuation by water vapor is not included in SLAM, while the attenuation due to oxygen is overestimated due to neglect of the interacting line mechanism. Once again the Lorentz profile results are very large. Table XIII shows the considerable variation of the Lorentz profile results with BOUND. These results can be attributed to the large low frequency tail from the Lorentz profile of lines at high frequencies.

LORENTZ PROFILE

FREQUENCY = 3.160 cm^{-1} U.S. STANDARD ATM., 1962 CONSTITUENT = 0

BOUND	HOR (dB/km)	UP (dB)
5.	0.0706	0.260
7.	0.0706	0.260
10.	0.0977	0.314
20.	0. 803	1.795
40.	2.26	4.80
80.	4.75	9.864
100.	6.25	12.92

VARIATION OF ATTENUATION WITH BOUND

TABLE XIII

VI. FURTHER REFINEMENTS REQUIRED

Several items which were not yet included in the program and which might have an appreciable effect on the attenuation are discussed below. In the SLAM program so far, we have neglected the continuum attenuation of nitrogen. Using the data of Gebbie, et. al.[18] we estimate the horizontal attenuation due to this cause at ground level to be about 1.5 dB/km at a frequency of 100 cm^{-1}, the peak of the nitrogen continuum absorption curve, and 0.2 dB/km at a frequency of 35 cm^{-1}. The nitrogen continuum should be included, but it is not likely to change the general shape of the attenuation curves. Several trace species having active rotational spectra are present in the stratosphere, and it is desirable to estimate the strengths of their absorption lines. These include nitrous oxide, nitric acid vapor, nitrogen dioxide, sulfur dioxide, and nitric oxide.[19]

A low-altitude effect that should be dealt with is the excess attenuation of water, beyond that calculated from the individual lines of the water monomer. This is especially noticeable in the troughs between the peaks of the water monomer absorption. This excess absorption can have three causes. The line profiles of the water monomer may be different from that assumed, leading to greater absorption in the wings of the lines, and hence in the troughs. Water dimers[20-23] can contribute their own spectrum of absorption, and lastly, short-lived collision complexes of the water molecule with the broadening molecule may induce a temporary electric dipole moment, leading to increased absorption. These three possible causes can be largely separated from each other by considering how they scale with the physical variables of the problem: water-vapor pressure, pressure of the external broadening gas, and temperature.

Various cases can be distinguished: If S is the integrated strength of a line and α its half-width at half-maximum, then at the center of an isolated line, the attenuation is proportional to S/α; in the wings, it is proportional to $S\,\alpha$; and for a group of lines with strength S that overlap due to the collisional broadening, it is S. For water monomers, S is proportional to the partial pressure of the water vapor; for dimers, it is proportional to the square of the partial pressure, and for collision complexes of water molecules with nitrogen, it is proportional to the product of the partial pressures of water vapor and nitrogen. Likewise, the quantity α is proportional to the partial pressures of nitrogen and water vapor for broadening by nitrogen and water vapor, respectively. For collisionally induced absorption, α is independent of any of the pressures. From the data of Burroughs, Jones, and Gebbie,[16] taken at 311 and 337 μm in pure water vapor, the attenuation is proportional to the square of the water vapor pressure. From the above scaling laws, this might be due either to attenuation from the wings of well-separated monomer lines or to overlapping dimer lines. However, the rapid change of attenuation with temperature was interpreted by these experimenters as evidence of water dimers.

At altitudes higher than about 40 km, Doppler broadening will be important. Its neglect imparts a spuriously large value to the attenuation at a line center at high altitudes because the attenuation at a line center varies inversely with the line width when Doppler broadening is neglected, while the pressure-broadened line width narrows with increasing altitude. The effect of the decrease in line width with altitude will tend to counterbalance the decreasing concentration, leaving a tendency to a spuriously constant attenuation at the center of a line. This effect has been allowed for in the SLAM program as described above. However the effect of Doppler broadening on the wings of the lines is not yet included. This would involve

combining the Doppler broadening with collisional broadening not only when the latter is described by the Lorentz profile but also when it is described by the Van Vleck-Weisskopf or Gross profiles. Another high-altitude effect that must be considered is Zeeman splitting of the oxygen lines.

At lower altitudes, the profile of two overlapping lines of a single molecular constituent is not necessarily equal to the sum of the profiles of the individual lines (as assumed in SLAM). This consideration is particularly important for the microwave spectrum of oxygen. Recent results suggest how this can be taken into account in the future.[24]

Finally, we note the influence of the method of integration upon the computed vertical attenuations. A rough calculation in one particular case showed an 8% difference between the results of the trapezoidal-rule integration and a higher-order method.

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APPENDIX

SLAM Program Listing

```
003C:   OK,00306314     01/13/76     13:47
      DIMENSION W(7,33), GNU(3000),S(3000),ALPHA(3000),EDP(3000)
      DIMENSION MOL(3000),CAY1(7),FNU(100)
      DIMENSION SUM1(7),BINBUF(4,40),IBINBUF(3,40)
      DIMENSION H(33),P(33),T(33),C1(33),C3(33)
      DIMENSION CS1(33),CS2(7,33),CA(33),AM(7),DOP(7),DOP1(7,33)
      DIMENSION DOWN(33,100),HOR(33,100),UP(33,100)
C     AM(M) REPRESENTS THE PART OF THE ATMOSPHERE BY VOLUME THAT CONSISTS
C     OF CONSTITUENT M
      DATA AM(2),AM(4),AM(5),AM(6),AM(7)/330.E-06,.28E-06,.075E-06,1.6
     2E-06,2.095E-01/
C     THE FOLLOWING PARAMETERS DEPEND ON THE MASS OF THE INDIVIDUAL
C     MOLECULES AND DETERMINE THE DOPPLER BROADENING
      DATA DOP(1),DOP(2),DOP(3),DOP(4),DOP(5),DOP(6),DOP(7)/
     21.013850E-7,4.484607E-8,6.208538E-8,6.484607E-8,8.128885E-8,
     31.075350E-7,7.603875E-8/
C     THE NEXT DATA REPRESENT THE CAPTIONS FOR THE VARIOUS
C     ATMOSPHERIC MODELS
      INTEGER MODEL(7,6)/
     2'MIDLATITUDE WINTER MODEL  ',
     3'       TROPICAL MODEL     ',
     4'MIDLATITUDE SUMMER MODEL  ',
     5'SUBARTIC WINTER MODEL     ',
     6'SUBARTIC SUMMER MODEL     ',
     7'U.S. STANDARD ATM.,1962   '/
      PI=3.14159
      IV=1
C     THE ATMOSPHERIC MODEL IS READ:HEIGHT IN KM,PRESSURE IN MB,TEMPERAT-
C     URE IN DEGREES KELVIN,WATER VAPOR AND OZONE CONTENT IN G/(M**3)
      READ(1,77)(H(I),P(I),T(I),C1(I),C3(I),I=1,33)
   77 FORMAT(F10.3,E10.4,F10.3,2E10.4)
C     W(M,N) IS THE NUMBER OF MOLECULES OF SPECIES M AT A HEIGHT REPRES-
C     ENTED BY N THAT IS CONTAINED IN A COLUMN OF ATMOSPHERE 1 KM IN
C     LENGTH AND 1 CM**2 IN CROSS SECTIONAL AREA
      DO 7 M=1,7
      DO 7 N=1,33
    7 W(M,N)=(.724270E+24)*P(N)*AM(M)/T(N)
      DO 8 N=1,33
      W(1,N)=C1(N)*3.346E+21
    8 W(3,N)=C3(N)*1.2546E+21
C
C     CHOICE OF PARAMETERS FOR THE CALCULATION ARE READ:INITIAL AND FINAL
C     FREQUENCY,FREQUENCY INCREMENT,RANGE OF FREQUENCY FOR WHICH LINES
C     ARE SUMMED,SHAPE OF LINE PROFILE,CONSTITUENT,AND CAPTION FOR
C     ATMOSPHERIC MODEL
      READ(3,85)V1,V2,DV,BOUND,LP,IC,MOD
   85 FORMAT(4F10.3,3I5)
      LP1=LP
      WRITE(111,87)V1,V2,DV,BOUND,(MODEL(KK,MOD),KK=1,7)
   87 FORMAT('V1=',F10.3,'V2=',F10.3,'DV=',F10.3,'BOUND=',F10.3,2X,6A4
     2,2A)
      VBOT=V1-BOUND
      VTOP=V2+BOUND
      I=1
      ILL=1
```

```
C
C     DATA ON SPECTRAL LINES ARE READ FROM A BINARY FILE
    1 READ(2)IREC,((BINBUF(JJ,K),JJ=1,4),(IBINBUF(JJ,K),JJ=1,3)
     2,K=1,IREC)
C     OPTIONAL STATEMENT FOR DOING CALCULATION IN DOUBLE PRECISION
X   1 CALL READDP(IREC,BINBUF,IBINBUF)
      TMAX=BINBUF(1,IREC)
      IF(TMAX.LT.VBOT)GO TO 1
      DO 9 K=1,IREC
      GNU(I)=BINBUF(1,K);S(I)=BINBUF(2,K);ALPHA(I)=BINBUF(3,K);
     2EOP(I)=BINBUF(4,K);MOL(I)=IBINBUF(3,K)
      IF(GNU(I).LT.VBOT)GO TO 9
      IF(GNU(I).GT.VTOP)GO TO 11
      I=I+1
    9 CONTINUE
      IF(I.GT.2960)I=I-1;GO TO 11
      GO TO 1
   11 I1=I
      WRITE(111,97)VBOT,VTOP,GNU(1),GNU(I1),I1
   97 FORMAT('VBOT',F12.3,'VTOP',F12.3,'GNU(1)=',F12.3,'GNU=',F12.3,'I1'
     2,I8)
      I5=1
      V2P=GNU(I1)-BOUND
      IB=1
      PO=1013.00
      TO=296.00
C
C     CB1(N) AND CB2(M,N) ARE FACTORS NECESSARY FOR THE CALCULATION OF
C     THE POPULATION FACTOR AND THE ROTATIONAL PARTITION FUNCTION AT
C     T(N),RELATIVE TO 296 DEGREES KELVIN
C
      DO 2 N=1,33
    2 CB1(N)=(TO-T(N))/(TO*T(N)*.6946)
      DO 21 M=1,7
      GO TO(17,19,17,19,19,17,19)M
   17 DO 3 N=1,33
    3 CB2(M,N)=((TO/T(N))**1.5)
      GO TO 21
   19 DO 4 N=1,33
    4 CB2(M,N)=TO/T(N)
   21 CONTINUE
C
C     FACTOR GIVING TEMPERATURE AND PRESSURE DEPENDENCE OF LINE WIDTH IS
C     COMPUTED AT EACH ALTITUDE
      DO 5 N=1,33
    5 CA(N)=((TO/T(N))**0.5)*(P(N)/PO)
C     DOP1(N1,N2) IS A FACTOR NECESSARY TO DETERMINE THE DOPPLER
C     BROADENING FOR A GIVEN MOLECULE AT A GIVEN ALTITUDE
      DO 372 N1=1,7
      DO 372 N2=1,33
  372 DOP1(N1,N2)=DOP(N1)*T(N2)**.5
      SUM=0.0
      SAVE=0.0
      V=V1
C
```

```
C     START OF COMPUTATION OF ATTENUATION AT A FIXED ALTITUDE AND
C     FREQUENCY
C
C     FIRST THE INDEX OF THE LINES THAT LIE WITHIN PLUS OR MINUS BOUND
C     OF THE FREQUENCY OF INTEREST ARE DETERMINED
   25 DO 33 I=I5,I1
      IF(V-BOUND-GNU(I))29,29,33
   29 I5=I
      GO TO 35
   33 CONTINUE
      I5=I1
      GO TO 53
   35 DO 39 J=I5,I1
      IF(V+BOUND-GNU(J))37,37,39
   37 I6=J-1
      GO TO 43
   39 CONTINUE
      I6=I1
   43 DO 6 N=1,33
      DO 27 M=1,7
      CAY1(M)=0.0
   27 SUM1(M)=0.0
      DO 23 I=I5,I6
      M=MOL(I)
      SS=S(I)*CS2(M,N)*(EXP(-EOP(I)*CS1(N)))*(1.-EXP(-4.86378E-03*GNU(
     2I)))
C     IF IC=0 ALL CONSTITUENTS ARE TAKEN INTO ACCOUNT,IF IC=M ONLY
C     CONSTITUENT M,IF IC=-M ALL BUT CONSTITUENT M
      IF(IC.GT.0.AND.M.NE.IC.OR.IC.EQ.(-M))SS=0
      ALPHA1=ALPHA(I)*CA(N)
      M=MOL(I)
      Z=V-GNU(I)
      LP=LP1
C     IF THE FREQUENCY AT WHICH THE ATTENUATION IS COMPUTED IS
C     WITHIN .0005 CM**-1 OF A LINE THE VOIGT PROFILE AT THE CENTER
C     OF THAT LINE IS USED AND THIS FACT IS OUTPUT
      IF(ABS(Z).LE..0005.AND.N.EQ.1)OUTPUT(108)Z
      IF(ABS(Z).LE..0005)LP=4
      Z1=V+GNU(I)
C
C     BRANCH TO DIFFERENT CALCULATIONS DEPENDING ON LINE SHAPE
      GO TO(200,201,202,203),LP
C     LORENTZ LINE SHAPE
  200 SUM1(M)=SS*ALPHA1/(Z**2+ALPHA1**2)
      GO TO 225
C     VAN-VLECK WEISSKOPF LINE SHAPE
  201 VVWF=(1/(Z**2+ALPHA1**2))+(1/(Z1**2+ALPHA1**2))
      SUM1(M)=(SS*ALPHA1*(V**2)/(GNU(I)**2))*VVWF
      GO TO 225
C     'KINETIC'(GROSS/ZHEVAKIN-NAUMOV) LINE SHAPE
  202 GR=((Z*Z1)**2)+(4.*(V**2)*(ALPHA1**2))
      SUM1(M)=SS*ALPHA1*4.*(V**2)/GR
      GO TO 225
C     NEXT THE DOPPLER WIDTH FOR THE GIVEN LINE IS CALCULATED
  203 BETA=GNU(I)*DOP1(M,N)
```

```
C     THE NEXT PARAMETER DEPENDS ON THE RATIO OF THE COLLISIONALLY
C     BROADENED WIDTH TO THE DOPPLER WIDTH
      Y=ALPHA1/BETA
C     DEPENDING ON THE ABOVE PARAMETER EITHER AN ASYMPTOTIC FORMULA
C     FOR THE VOIGT PROFILE AT THE CENTER OF A RESONANCE LINE IS USED
C     OR A POLYNOMIAL APPROXIMATION FOR THE PROBABILITY INTEGRAL IS
C     ADOPTED
      IF(Y.GE.5.)GO TO 204
      TY=1./(1.+.3275911*Y)
      TY2=TY*TY
      TY3=TY2*TY
      TY4=TY3*TY
      TY5=TY4*TY
      SUM1(M)=SS*1.772454*(.2548296*TY=.2844967*TY2+1.421414*TY3
     2=1.453152*TY4+1.061405*TY5)/BETA
      GO TO 225
  204 Y2=Y*Y
      Y3=Y2*Y
      Y4=Y3*Y
      Y5=Y4*Y
      Y6=Y5*Y
      Y7=Y6*Y
      Y8=Y7*Y
      Y9=Y8*Y
      SUM1(M)=SS*(1./Y=.5/Y3+.75/Y5=1.875/Y7+6.5625/Y9)/BETA
  225 CAY1(M)=CAY1(M)+SUM1(M)
   23 CONTINUE
      CAY=0.0
      DO 47 M=1,7
   47 CAY=CAY+CAY1(M)*W(M,N)
      OPD=CAY*1.38240
      IF(N.EQ.1)GO TO 10
C
C     NEXT THE ATTE[illegible]ON AT THE VARIOUS LEVELS IS SUMMED
      SUM=SUM+.5*([illegible](N=1))*(OPD+SAVE)
   10 DOWN(N,IV)=SU[illegible]K(N,IV)=OPD
      SA[illegible]OPD
    6 C[illegible]NUE
      FR[illegible](IV)=V
      DO 109 N=1,33
  109 UP(N,IV)=SUM=DOWN(N,IV)
      IF((V+DV).GT.V2P)GO TO 53
      IF((V+.5*DV).GE.V2)GO TO 53
      IF(IV.GE.100)GO TO 53
      IV=IV+1
C     THE FREQUENCY IS INCREMENTED AND THE CALCULATION PERFORMED AGAIN
      V=V1+(IV=1)*DV
      SUM=0.0
      SAVE=0.0
      GO TO 25
   53 GO TO(215,216,217),LP1
  215 WRITE(111,101)IV,V,V2P,IC
      GO TO 219
  101 FORMAT(I5,2F10.4,'   LORENTZ PROFILE',3X,'CONSTITUENT=',I5)
  216 WRITE(111,220)IV,V,V2P,IC
```

```
      GO TO 219
  220 FORMAT(I5,2F10.4,'   VAN VLECK-WEISSKOPF PROFILE',3X,'CONSTITUENT=
     2',I5)
  217 WRITE(111,221)IV,V,V2P,IC
  221 FORMAT(I5,2F10.4,'   GROSS PROFILE',3X,'CONSTITUENT=',I5)
  112 FORMAT(4I3,4F8.2,4X,I1,I3,'(G7.2)',10X,F8.2)
  219 FINAL=V1+99.*DV
      DO 107 J=1,IV
C
C     THE NEXT STATEMENTS GENERATE AN OUTPUT FILE TO BE USED AS INPUT FOR
C     A GRAPHICS ROUTINE CALLED GPLOT1D
      WRITE(109,110)10,0,0,0
  110 FORMAT(4I3,'HORIZONTAL AND VERTICAL MOLECULAR ATTENUATION')
      WRITE(109,111)10,0,0,0,(MODEL(KK,MOD),KK=1,7),FNU(J),BOUND
  111 FORMAT(4I3,6A4,A2,'FREQ=',F8.3,' CM**-1',' BOUND=',F7.3,' CM**-1'
     2)
      GO TO(210,211,212),LP1
  210 WRITE(109,124)10,0,0,0,IC
      GO TO 218
  124 FORMAT(4I3,'D=DOWN(DB)  U=UP(DB)  H=HOR(DB/KM)  LORENTZ',2X,'  CON
     2STITUENT=',I5)
  211 WRITE(109,214)10,0,0,0,IC
  214 FORMAT(4I3,'D=DOWN(DB)  U=UP(DB)  H=HOR(DB/KM)  VAN VLECK-WEISSKOP
     2F',3X,'CON=',I5)
      GO TO 218
  212 WRITE(109,213)10,0,0,0,IC
  213 FORMAT(4I3,'D=DOWN(DB)  U=UP(DB)  H=HOR(DB/KM)  GROSS',2X,'  CONST
     2ITUENT=',I5)
  218 WRITE(109,112)2,0,1,1,.7,70.,.2,.2,1,3,.1
      WRITE(109,150)2,90,1,1,1.,1000.,.2,.2,1,8,.1
  150 FORMAT(4I3,2F8.0,2F8.2,4X,I1,I3,'(G8.3)',10X,F8.2)
      WRITE(109,113)4,1,-1,0,-1,0,0
  113 FORMAT(7I3)
      WRITE(109,114)3,0,1,+30,0
  114 FORMAT(5I3)
      WRITE(109,115)(H(NN),NN=2,31)
  115 FORMAT(10F8.0)
  116 FORMAT(2I3)
      WRITE(109,151)3,90,1,+30,0,1,1,1.,1000.
      WRITE(109,122) DOWN(NN,J),NN=2,31)
  122 FORMAT(10(G8.3))
      WRITE(109,114)5,+2,68,0
      WRITE(109,151)3,90,1,+30,0,1,1,1.,1000.
      WRITE(109,122)(UP(NN,J),NN=2,31)
      WRITE(109,114)5,+2,85,0
      WRITE(109,154)2,0,1,1,.7,70.,3,3,1,1,.1
  154 FORMAT(4I3,4F8.2,4X,I1,I3,'(I1,-X,'' '')',5X,F8.2)
      WRITE(109,113)4,-2,0,0,0,0,0
      WRITE(109,152)2,90,1,1,.1,100.,.2,.2,1,7,.1
  152 FORMAT(4I3,2F8.2,2F8.2,4X,I1,I3,'(4X,G7.2)',7X,F8.2)
      WRITE(109,113)4,0,-2,0,0,0,0
      WRITE(109,151)3,90,1,+30,0,1,1,.1,100.
  151 FORMAT(7I3,2F8.2)
      WRITE(109,123)(HOR(NN,J),NN=2,31)
  123 FORMAT(10(G8.3))
```

```
      WRITE(109,114)5,+2,72,0
      WRITE(109,153)12,2,2,0,0,938,485
  153 FORMAT(5I3,2F8.0,'        DB PER KM')
      WRITE(109,117)12,0,2,1,0,200,15
  117 FORMAT(5I3,2I8,'VERTICAL HEIGHT(KM)')
      WRITE(109,118)12,2,2,+1,0, 5,665
  118 FORMAT(5I3,2I8,'ATTENUATION  DB')
      WRITE(109,116)1
C
C     THE NEXT STATEMENTS GENERATE A TABULAR OUTPUT
      WRITE(111,106)FNU(J)
  106 FORMAT('FREQUENCY=',F10.3)
      WRITE(111,104)
  104 FORMAT(2(' HEIGHT       HOR         DOWN          UP      '))
  107 WRITE(111,105)(H(NN),HOR(NN,J),DOWN(NN,J),UP(NN,J),NN=1,33)
  105 FORMAT(2(F10.3,3E12.5))
      IF((V+.5*DV).GE.V2)GO TO 75
      IF((V+DV).GT.V2P)GO TO 67
      IF(V.GE.FINAL)GO TO 63
      GO TO 75
   63 V1=FINAL+DV
      IS=1
      IV=1
      V=V1
      GO TO 25
C
C     NEXT THE DATA FROM THE DATA FILE  WILL BE REORGANIZED AND THE FILE
C     WILL BE READ AGAIN
   67 IV=1
      V1=V+DV
      VBOT=V1-BOUND
      DO 69 IN=1,I1
      IF(GNU(IN).GT.VBOT)GO TO 71
   69 CONTINUE
      IN=I1
   71 IJ=IN
      L=1
      DO 73 I=IJ,I1
      GNU(L)=GNU(I)
      S(L)=S(I)
      ALPHA(L)=ALPHA(I)
      EOP(L)=EOP(I)
      MOL(L)=MOL(I)
   73 L=L+1
      I=L
      ILL=L
      GO TO 1
   75 CALL EXIT
      END
```

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A computer program (SLAM) is described which calculates the attenuation by air of microwave and submillimeter wave radiation. Besides the horizontal attenuation, the vertical attenuation from various levels down to the ground and out into space is calculated for fixed frequency. The line profile and atmospheric model can be selected from among several. Comparison is made with other calculations and with experiment

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